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RESEARCH MEMORANDUM

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF COMPRESSOR INTERSTAGE AIR BLEED ON PERFORMANCE CHARACTERISTICS OF A 13-STAGE AXIAL-FLOW COMPRESSOR

By James G. Lucas, Richard P. Geye, and Howard F. Calvert

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF COMPRESSOR INTERSTAGE AIR BLEED ON PERFORMANCE CHARACTERISTICS OF A 13-STAGE AXIAL-FLOW COMPRESSOR

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SUMMARY

An analytical and experimental investigation was conducted on a modified production 13-stage axial-flow compressor to determine the effects of air bleed over the fifth- and tenth-stage rotor-blade rows on compressor over-all performance and rotating-stall characteristics. Although the quantitative results of the two phases of the investigation differed somewhat, the qualitative results showed the same trends.

Experimentally it was determined that the maximum speed at which rotating stall was encountered along the rated operating line was decreased from 69.8 percent of design with no bleed to 58.7 percent with maximum fifth-stage bleed flow, to 63.2 percent with maximum tenth-stage bleed flow, and to less than 50 percent with the combination of the two maximum bleed flows. In addition, the number of rotating-stall zones was changed from three, which was the pattern exciting dangerous rotor-blade resonant vibrations, to four or five, which did not excite such vibrations.

The experimental results also showed that bleed causes a compressor-discharge weight flow loss above about 75 percent of design speed, although over-all pressure ratio is almost unaffected, the combination bleed causing a small loss above about 75 percent speed. Fifth-stage bleed, either alone or in combination, gives a slight rise in low-speed efficiency, while tenth-stage bleed, either alone or in combination, gives a slight drop in efficiency at high speeds.

INTRODUCTION

One of the serious problems encountered in the use of high-pressure-ratio axial-flow compressors for turbojet engines is the deterioration of compressor over-all performance in the intermediate-speed range with the accompanying rotating-stall patterns. The rotating-stall zones can, at certain speeds in this range, be in resonance with the natural bending frequency of one or more of the compressor blade rows. This can cause serious vibrations in the affected blading, often with failure as the result (ref. 1). In addition, the poor intermediate-speed-range performance adversely affects the compressor surge-limit line, thereby reducing the acceleration margin between this line and the steady-state operating line. This increases the length of time required to accelerate through this range, a poor feature in itself, and, in turn, forces the engine to operate with rotating stall, and consequent blade vibrations, for a longer period of time. 4254

Recently, much analytical and experimental work has been directed toward the related problems of rotating-stall elimination and faster acceleration. The approach to this work is based on the fact that, at speeds well below design, the exit stages of the compressor choke and thereby limit the inlet flow. With the inlet stage forced to operate at a less-than-desirable flow, the incidence-angle level on the first rotor is increased to the point of stall and beyond. This causes rotating stall to develop; and further reductions of flow and speed rapidly lower the compressor pressure-producing capacity, thus lowering the surge-limit line. The work done so far has considered the effects of annular inlet blockage to destroy the periodic nature of the stall (ref. 2) and adjustable inlet guide vanes to alter the incidence-angle level at the first stage (ref. 3). In addition, consideration has been given to the effects of compressor-discharge air bleed on matching of turbine and compressor components as a means of decreasing acceleration times (ref. 4).

Compressor interstage air bleed has been analytically investigated (ref. 5) as a method to improve intermediate-speed stall and performance characteristics of a 16-stage axial-flow compressor. Because of the promise shown by this method, an analytical and experimental investigation was undertaken on the 13-stage compressor used for the investigations of references 1 to 3. It should be emphasized that this compressor did not have an acceleration problem, but did have a serious blade-vibration problem at intermediate speeds. In this investigation, no attempt has been made to evaluate the effects of interstage bleed on engine acceleration, fuel consumption, or thrust. The effects of such bleed were determined only on the stall-excited blade vibrations (ref. 6) and on the rotating stall and compressor over-all performance as reported herein.

The investigation was conducted in a sea-level test stand at the NACA Lewis laboratory, with the compressor being tested as a component of a modified production turbojet engine. The compressor used was a commercial 13-stage axial-flow unit having a design total-pressure ratio of about 7 with approximately 120-pound-per-second airflow at a speed of 8300 rpm. The compressor was equipped, for this investigation only, to allow air to be bled over the fifth- and tenth-stage rotor-blade rows either separately or together.

PRELIMINARY ANALYSIS

An analysis was performed on the compressor to determine if the occurrence of rotating stall could be delayed to a speed low enough to avoid the possibility of stall-excited blade vibrations with an attainable amount of bleed area. This analysis used stage-group data previously obtained from tests of another compressor of the same type used for the present investigation (ref. 7). These data were used with a stage-stacking system similar to that of reference 8 to obtain compressor over-all performance maps using constant-area interstage bleed before the fifth and tenth stages. The bleed air was assumed to be dumped to the atmosphere at compressor-inlet conditions, and an orifice-discharge coefficient of 0.4 was assumed for the bleed slots. The bleed slots were sized to allow the maximum amount of bleed area consistent with the requirements of casing rigidity and space for necessary and immovable engine accessories. Because the axial distance between adjacent stages was very small, the actual slots were machined over the fifth- and tenth-stage rotor-blade rows. In the stage-stacking analysis, however, it was necessary to assume that the bleed occurred between stages and also that the performance of the following stage group was unaffected by the bleed. It was expected that the spacing of the slots for each bleed around only two-thirds of the circumference would induce asymmetry of flow around the annulus into the following stages. However, it was assumed that such flow would not affect the performance of the later stages.

On each of the computed compressor performance maps, a rated-exhaust-nozzle-area equilibrium operating line was located by a method similar to that presented in reference 9. The boundary of rotating-stall occurrence along the operating line at each bleed condition was determined by the intersection of this line with the inlet-stage stall line, which was a plot of the points at which the first stage reached its flow coefficient for peak equivalent pressure ratio.

The analysis indicated that an appreciable decrease in the maximum speed at which rotating-stall exists could be realized with interstage bleed as shown on figure 1, which is a plot of bleed flow as a percent of inlet weight flow against corrected speed for the three bleed conditions, fifth-stage bleed, tenth-stage bleed, and the combination of the two. The points of rotating-stall occurrence marked on this figure show that stall occurs at 74.7 percent speed with no bleed, at 64.5 percent speed with fifth-stage bleed, at 69.8 percent speed with tenth-stage bleed, and at 57.3 percent speed with the combination bleed.

APPARATUS AND INSTRUMENTATION

A commercial axial-flow turbojet engine was modified for use in this investigation. The compressor casing was machined over the fifth- and

tenth-stage rotor-blade rows to allow air to be bled from the interior in a radially outward direction. Figure 2 shows sectional views of the casing with the bleed-slot configurations outlined. Consideration was given to the circumferential spacing of the segments of each slot in order to prevent any possible resonance between the natural bending frequencies of the rotor blades below these slots and the periodic blade force caused by rotation past the slot segments. This was done to avoid resonant excitation of vibrations in these blades from this source. The slots were rounded slightly at the interior of the casing, the inner edges having a radius of about 1/8 inch. Actual bleed areas at the fifth- 4254
and tenth-stage locations are 46.7 and 20.6 square inches, respectively. These bleed areas are such that, with the assumed orifice-discharge coefficient of 0.4, about 9 to 16 percent of the inlet flow could be bled from the two areas separately, as shown in figure 1.

Figure 3 shows two views of the machined casing, during the engine assembly procedure, both with and without the associated collectors. The bleed air leaving the collectors was ducted through separate orifices and control valves to the engine exhaust muffler. The amount of bleed flow could be regulated individually by the valves and was measured with thin-plate orifices.

The engine was equipped with an adjustable exhaust nozzle to permit a range of variation of the compressor operation at any given speed. The nozzle was sized such that, at its open position, the area was equivalent to the design area and the engine would operate at rated temperature ratio.

The instrumentation used to measure the over-all performance of the compressor is diagrammed in figure 4. Additional instrumentation needed to measure the bleed flow rates consisted of a single total-head tube, two unshielded thermocouples, and two orifice flange static-pressure taps in each orifice run. Rotating stall was detected and measured by hot-wire anemometer probes which were traversed radially by probe actuators in each of the first three stator-blade rows.

PROCEDURE

The investigation was conducted on a static test stand with the engine drawing in atmospheric air from the test cell at ambient conditions and discharging through a muffler to the atmosphere.

The compressor was operated at constant equivalent speeds from 50 to 100 percent of design without bleed, and up to 85 percent with bleed, at increments of 5 percent. The speed range investigated with bleed was extended to somewhat higher speeds than would probably be used in order to adequately determine the performance trends. At each of the speed and bleed conditions where possible, the exhaust-nozzle size was varied from design in order to cover a range of compressor-inlet weight flow. The range of flows obtainable at any given speed was small because of turbine temperature limits.

Data for the present report were taken, for each of the bleed conditions, with the appropriate control valve, or valves, open fully to simulate an application condition where the air bled would be dumped to the atmosphere.

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RESULTS AND DISCUSSION

The over-all performance of the test compressor without bleed and with each of the three bleed conditions is shown on figure 5 as curves of adiabatic temperature-rise efficiency and over-all total-pressure ratio against inlet equivalent weight flow at various percentages of corrected design speed. The points obtained with rated exhaust-nozzle setting are shown as solid symbols on these figures. It should be noted that, for operation with bleed, compressor efficiency is the ratio of output power, based on discharge weight flow and over-all pressure ratio, to input power, based on bleed weight flow and its enthalpy rise and discharge weight flow and its enthalpy rise.

In order to provide a comparison of the over-all performance and rotating-stall characteristics of the compressor under the four test conditions, figure 6 presents curves of over-all total-pressure ratio, adiabatic temperature-rise efficiency, discharge weight flow corrected to inlet conditions, and bleed weight flow as a percentage of inlet flow plotted against corrected speed, all at the rated exhaust-nozzle setting only. Also shown are the speed range over which rotating stall is encountered and the number of rotating-stall zones.

On figure 6 it can be seen that the maximum speed at which rotating stall was encountered has been noticeably decreased by use of interstage bleed. With no bleed, the maximum speed is 69.8 percent of design; with fifth-stage bleed, it is 58.7 percent; with tenth-stage bleed, it is 63.2 percent; and with the combination bleed, it is something less than 50 percent, which was the lowest speed investigated. These figures run from about 5 percent to something over 7 percent lower than the corresponding predicted points shown on figure 1. The reason for this discrepancy arises from the fact that, while the test compressor was the same type as that on which the analysis was performed, there were sufficient differences in the stage group characteristic curves and amounts of bleed to change the inlet-stage stall points to lower speeds. With no bleed, there were three stall zones present up to about 63 percent speed and an unsteady four or five zones over the rest of the stall range. With either fifth- or tenth-stage bleed, there was an unsteady four- or five-zone rotating-stall pattern over the entire measured

stall range. Reference 6 shows that the two blade rows most susceptible to dangerous resonant vibrations are excited by the three-zone rotating-stall pattern at about 60 and 68 percent of rated mechanical speed. Inasmuch as three-zone stall was nonexistent with any of the bleed conditions investigated, such resonant vibrations could not be excited. Even with tenth-stage bleed, which did not eliminate rotating stall to below the lowest critical speed (60 percent) at sea level, the character of the stall was changed in such a manner as to preclude resonant blade-vibration 4254
excitation. The unsteady four- or five-zone stall patterns prevalent with fifth- and tenth-stage bleed did not excite vibration in any other of the susceptible rows, nor were they in resonance with either of the two blade rows which were vibrating at 60 and 68 percent speed with no bleed.

The curves on figure 6 showing discharge weight flow corrected to compressor-inlet conditions indicate that, up to about 75 percent speed, the discharge flow does not vary more than about 2 to 3 pounds per second among the four test conditions. Above this speed, however, the flows with bleed begin to diverge from the no-bleed flow; and at 85 percent speed the lowest flow, with the combined bleed, has fallen about 9 pounds per second or about 10 percent below the no-bleed flow. This means that the engine would suffer a thrust penalty under such conditions, although possibly a portion of the loss could be recovered by a suitable method of dumping the bleed air overboard.

The curves of adiabatic temperature-rise efficiency show that fifth-stage bleed, compared with the no-bleed case, gives about a 4-point boost to efficiency at low speed, decreasing to the same efficiency at 80 percent speed. Tenth-stage bleed gives about the same efficiency at low speeds as with no bleed, but suffers about a 3-point drop at 85 percent speed. With the combination bleed, low-speed efficiency is improved over that with no bleed by about 3 points but suffers at 85 percent speed by about 5 points.

The compressor over-all total-pressure ratio is not affected by either of the individual bleeds to any degree, although the combination bleed does cause a small dropoff in pressure ratio at speeds above about 75 percent.

A comparison of the bleed weight flow curves with the corresponding analytical ones on figure 1 shows that only about three-fourths of the predicted bleed flow was actually obtained experimentally. This indicates that the orifice-discharge coefficient of 0.4 used for the analysis was too high and should have been about 0.3. Actually, a fixed coefficient is not completely satisfactory because, as the compressor operating point is changed, the flow conditions across the slot, normal to the bleed flow direction, are changing.

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CONCLUDING REMARKS

In this investigation compressor interstage air bleed was primarily intended to move the rotating-stall-operation regime to a lower-speed range and thus prevent critical resonant blade vibrations from this source, and the results seem to be quite successful. For the particular compressor investigated, the use of either bleed system separately would either remove or alter the rotating-stall pattern in the critical-speed range to allow vibration-free operation. However, all compressors of a given type do not have the same performance characteristics in the intermediate-speed range, as evidenced by the different maximum speeds at which rotating stall was encountered for the test compressor and the one on which the analysis was performed. An even more serious problem in this speed range is the possible difference in the number of rotating-stall zones among compressors of the same type. Therefore, it would seem wise in a production version to allow for the extremes of performance and use the combination bleed which completely eliminates stall down to at least 50 percent speed, well below the speed range where dangerous vibrations would occur. As the engine speed is increased, one of the bleed ports could be closed inasmuch as the combination bleed gives the poorest performance above about 75 percent speed. Inasmuch as the tenth-stage bleed gives the poorer performance (lower discharge flow, lower efficiency, and higher stall-speed limit) of the two individual bleeds, it would probably be the one to be closed, leaving the fifth-stage bleed open until a speed was reached where the poorest compressor of a series would be out of the rotating-stall range. In selecting the bleed schedule to be used, the speeds used should be corrected speeds, because the rotating-stall limit is a function of corrected speed.

In using interstage bleed to alleviate a serious rotating-stall condition, consideration must be given to the effects of such bleed on the engine acceleration rate through the intermediate-speed range. Although reference 5 indicates that such bleed could well increase this rate, it would seem possible for excessive bleed rates, or excessively high-speed use of the bleed, to decrease the acceleration rate.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 25, 1956

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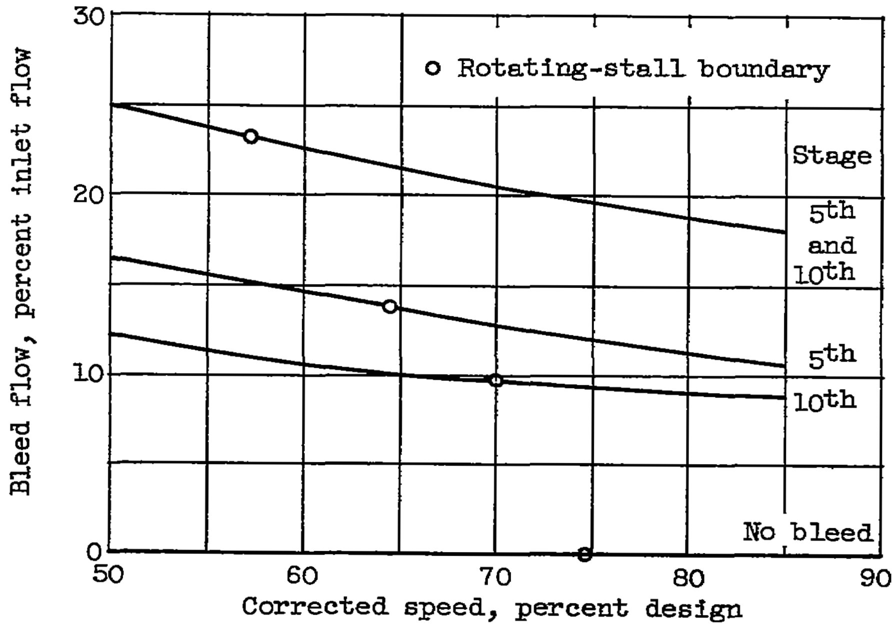

Figure 1. - Predicted percentage of bleed along rated operating line.

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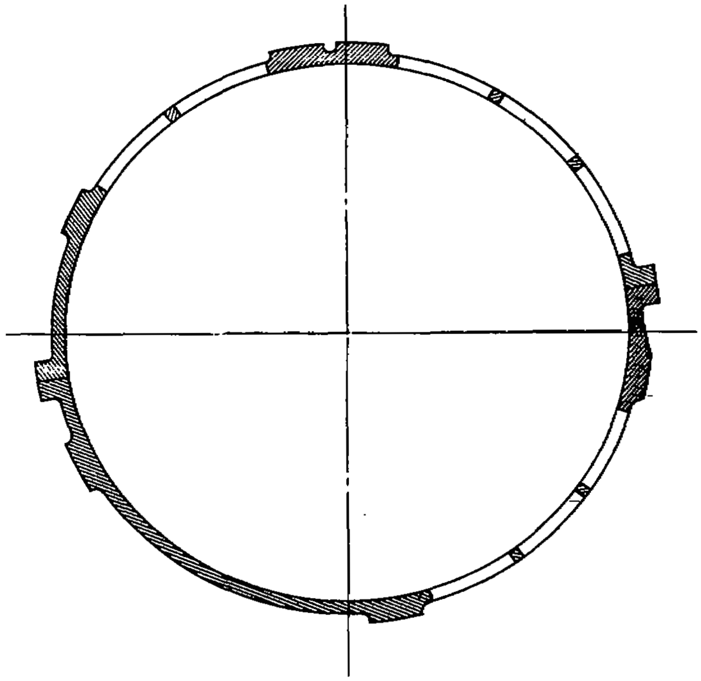
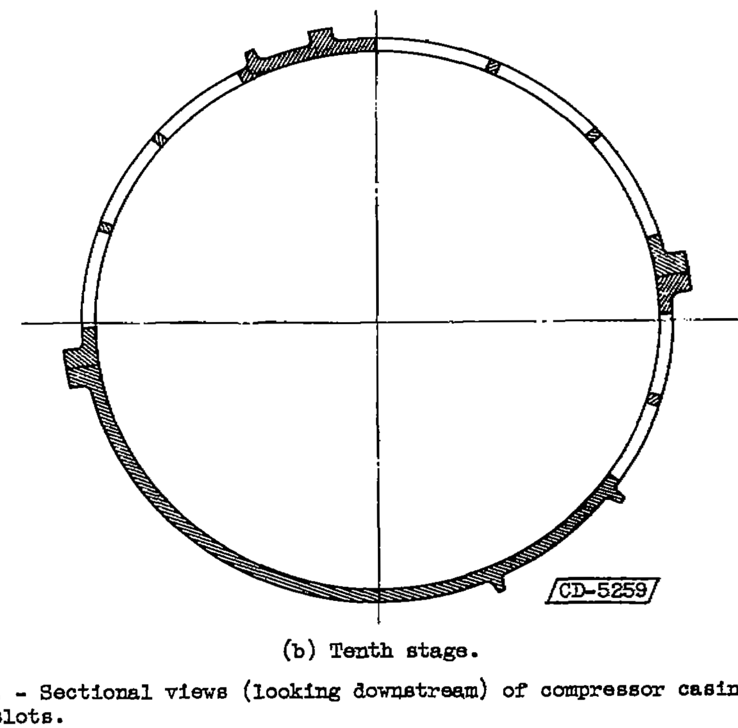


(a) Fifth stage.



(b) Tenth stage.

Figure 2. - Sectional views (looking downstream) of compressor casing showing bleed slots.

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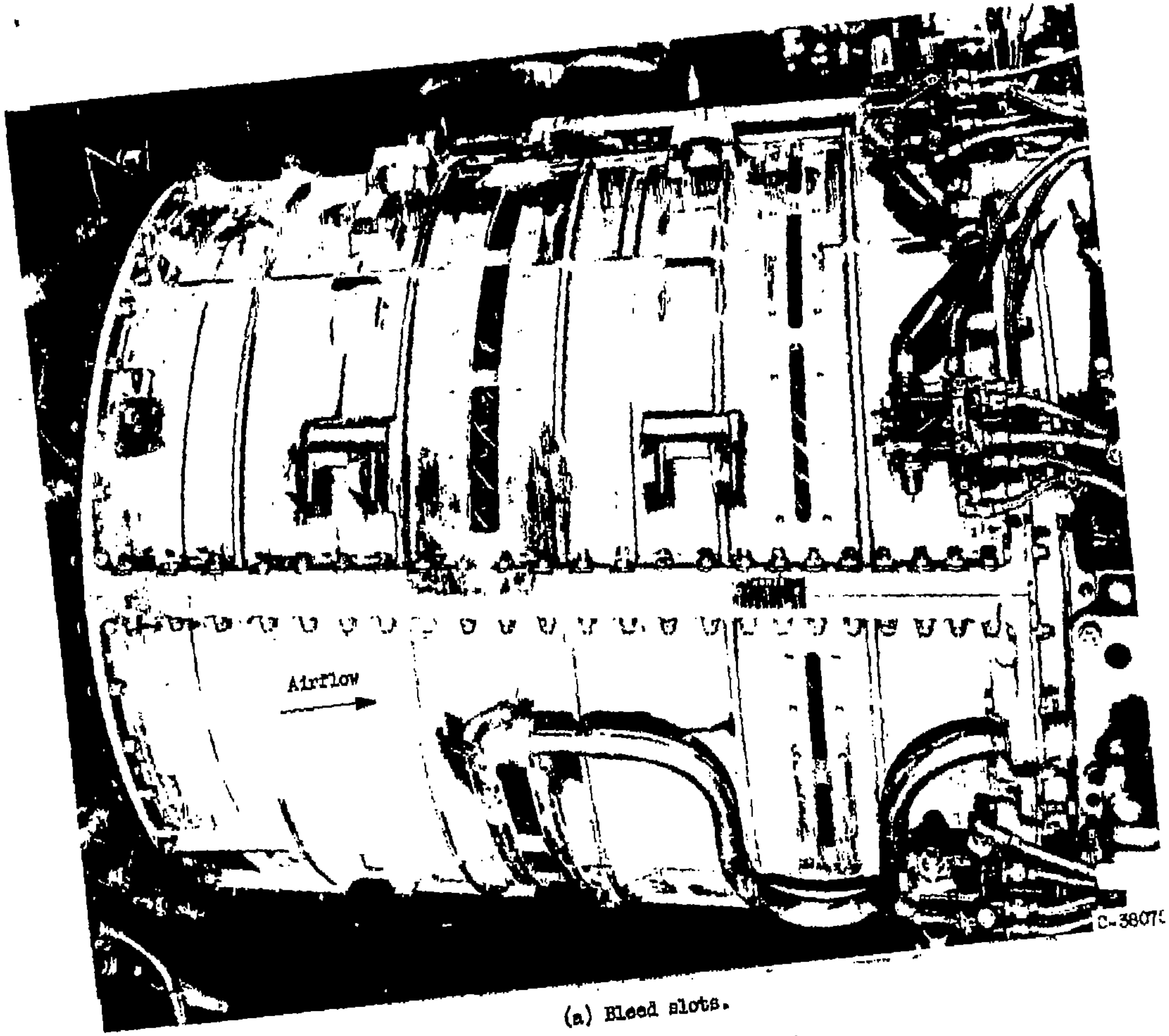
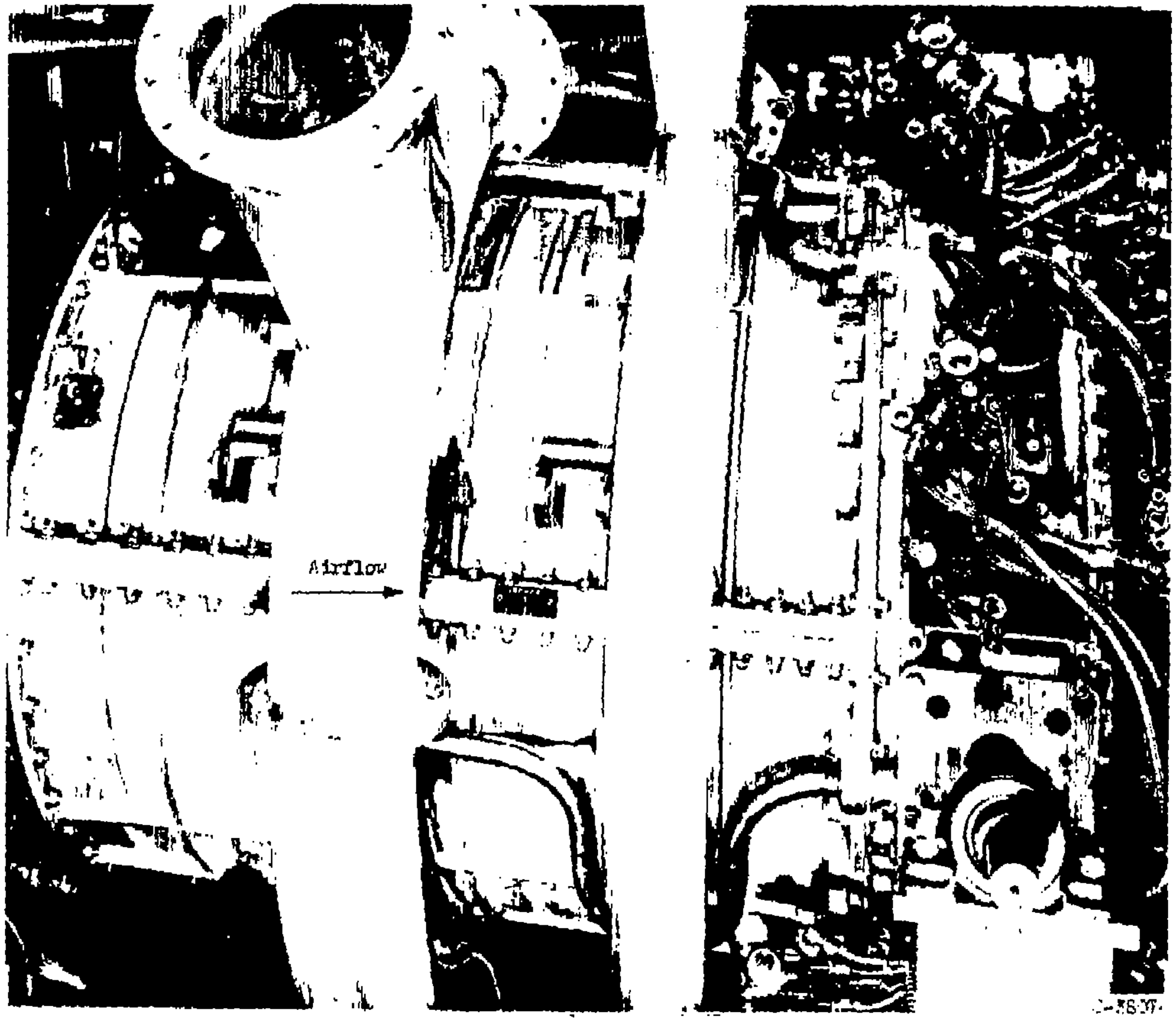


(a) Bleed slots.

Figure 3. - Compressor casing.



(b) Bleed manifolds.

Figure 3. - Concluded. Compressor casing.

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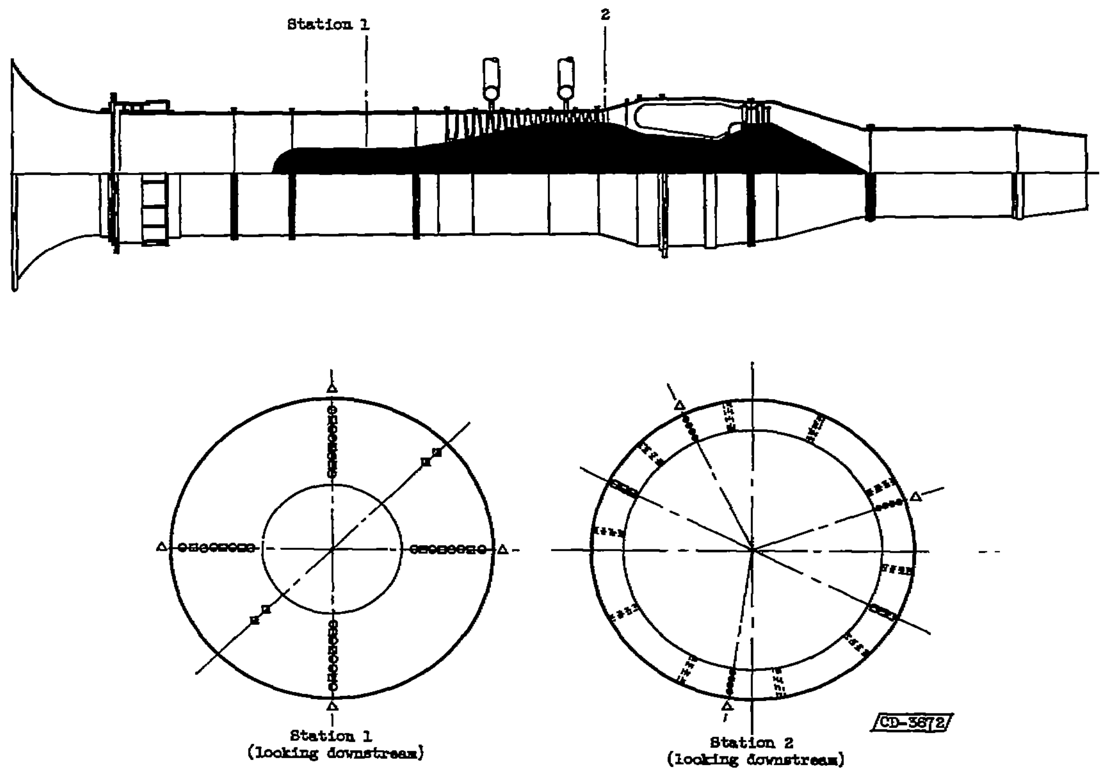

	Type of probe	Number of probes per station, at station -	
		1	2
○	Total pressure	15	12
□	Temperature	12	6
◇	Stream static pressure	4	0
△	Wall static pressure	4	3

Figure 4. - Schematic diagram of compressor over-all performance instrumentation.

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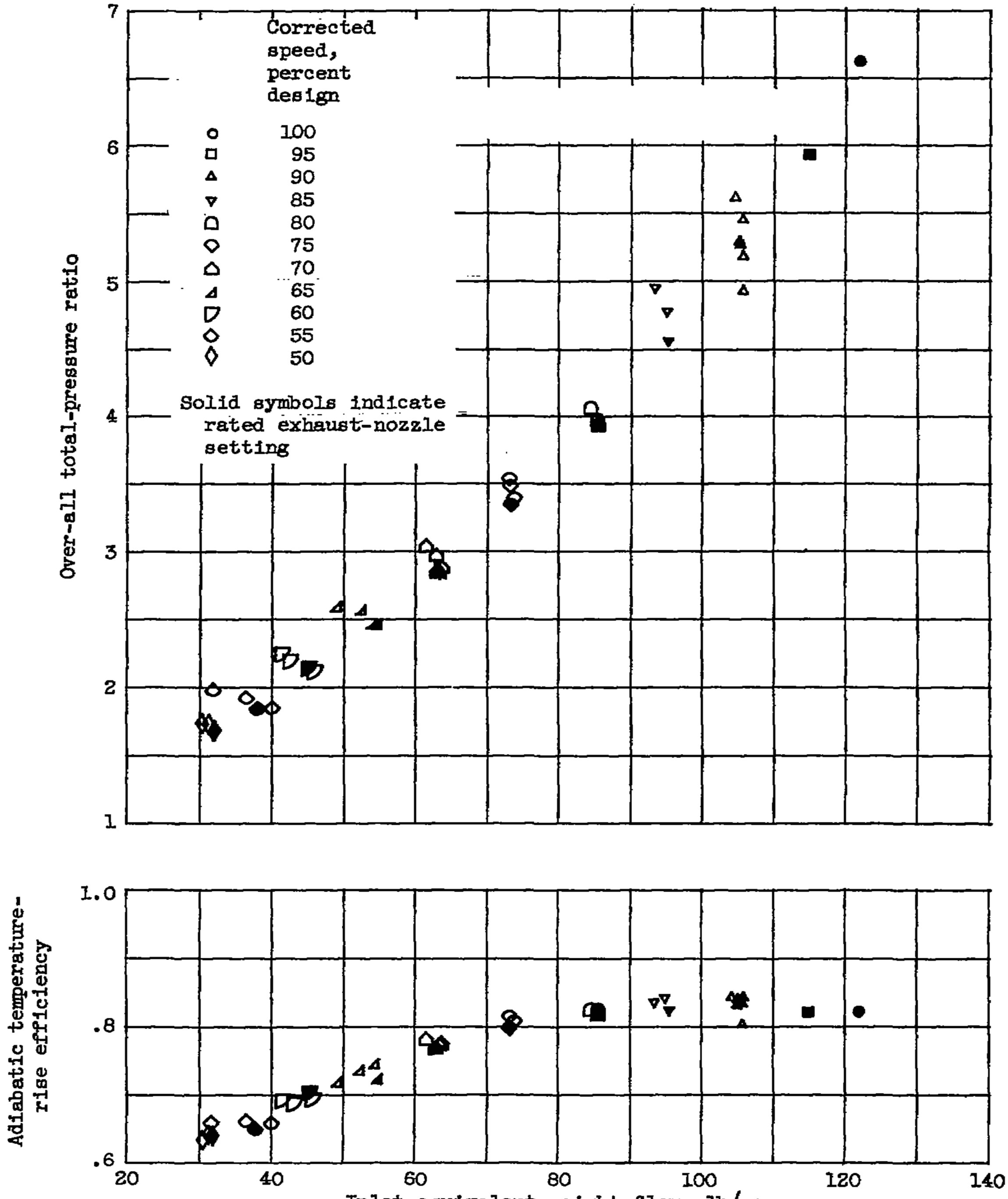

(a) No bleed.

Figure 5. - Compressor over-all performance.

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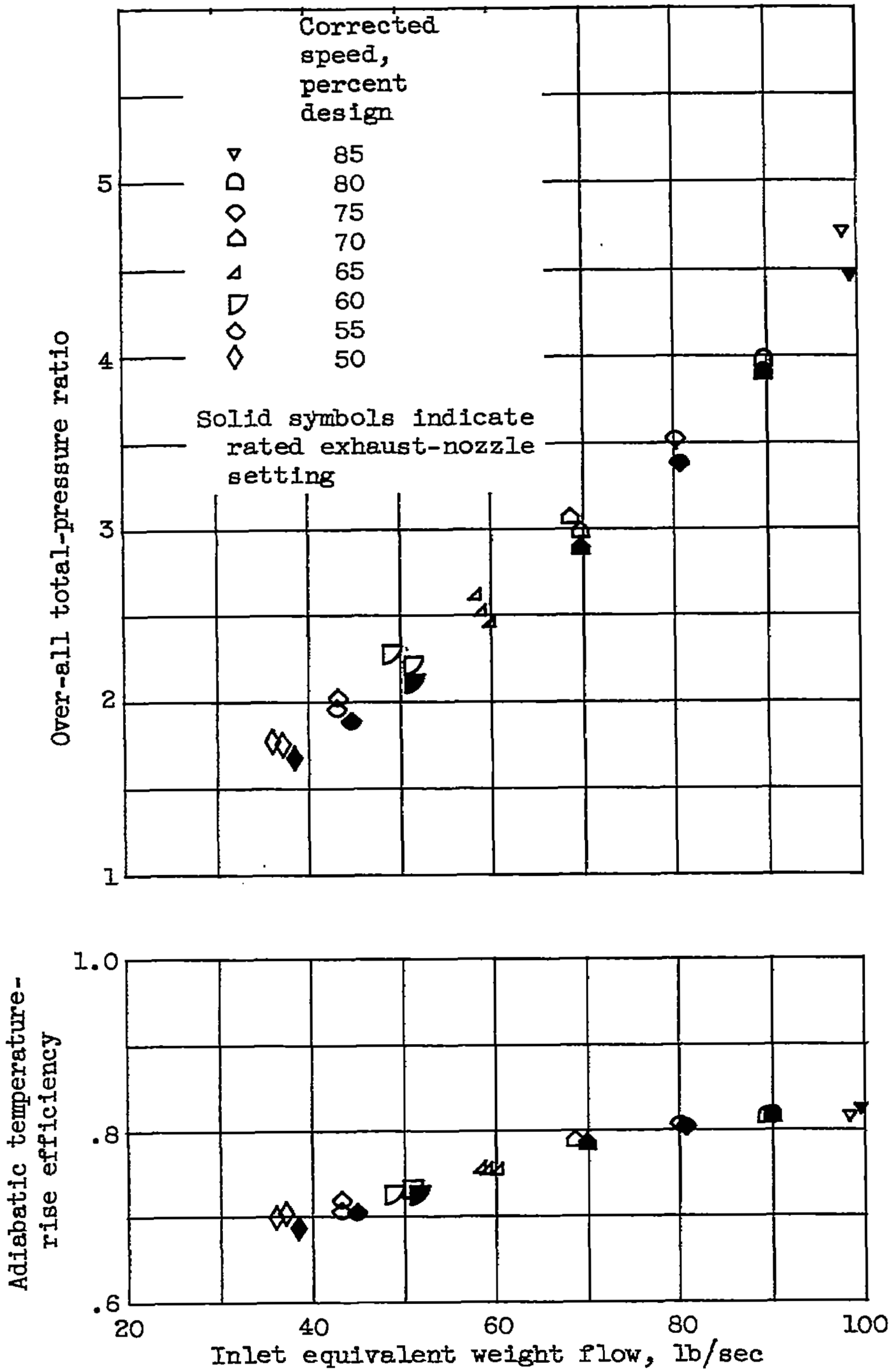

(b) Fifth-stage bleed.

Figure 5. - Continued. Compressor over-all performance.

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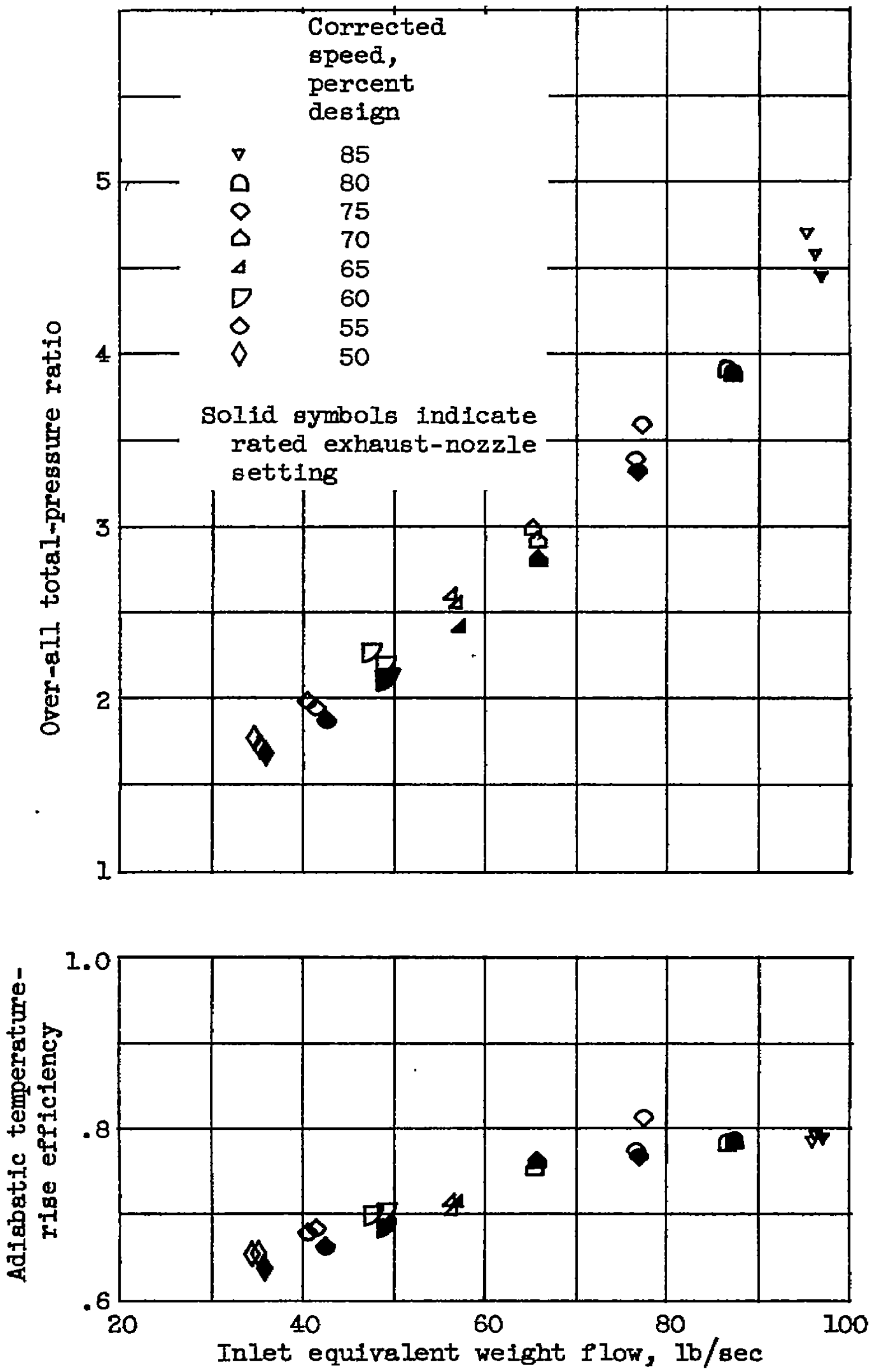

(c) Tenth-stage bleed.

Figure 5. - Continued. Compressor over-all performance.

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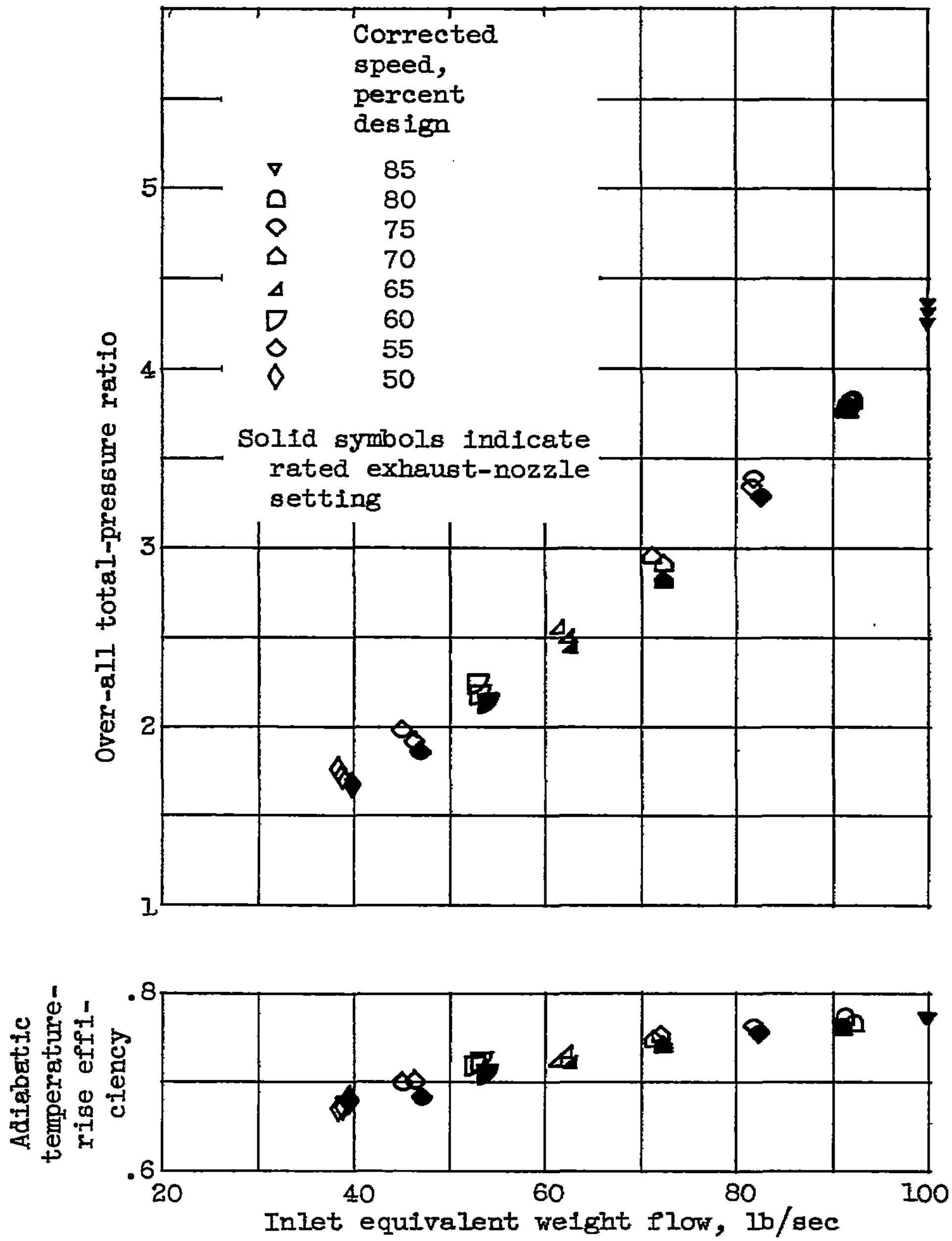

(d) Fifth- and tenth-stage bleed.

Figure 5. - Concluded. Compressor over-all performance.

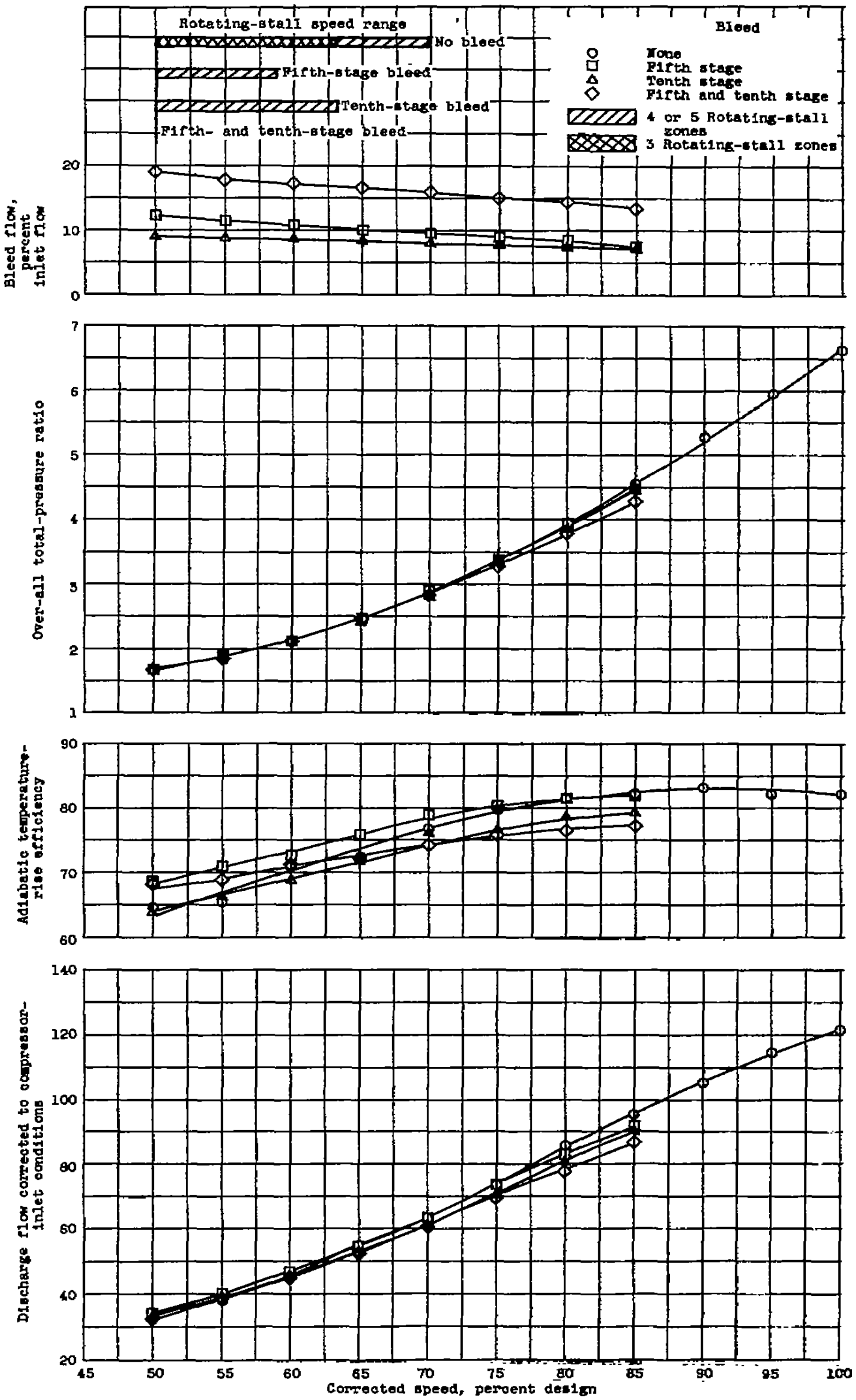

Figure 6. - Over-all compressor performance and rotating-stall speed range with and without interstage bleed at rated exhaust-nozzle setting.

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